INTERPRETATION OF INDEX PROPERTIES

OF THE UNIFIED CLASSIFICATION SYSTEM FOR HAWAIIAN SOILS

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INTRODUCTION

Of all engineering materials, soil is most frequently used and in greatest abundance. From prehistoric times, man has built his shelters in, from, and on this readily available natural material. His early knowledge of soil was learned from experience handed down from previous generations and from trial-and-error procedures (Holtz, 1969).

Early builders had considerable knowledge of foundation properties of soils. This is attested by the famous pyramids of Egypt, the Great Wall of China, and earth dams in India that have been storing water for more than 2000 years. However, numerous failures have also occurred because of the inadequacy of soil foundations. Among the most famous is the Campanile at Pisa, Italy, known as the Leaning Tower of Pisa (Soil Survey Staff, 1966). Many other failures due to inadequate soil investigations are recorded in literature whereby countless lives and millions of dollars have been lost.

The need for more substantial structures caused engineers to study soil problems and to analyze them in the light of other structural design problems. One of the first theoretical approaches to solving soil problems was made by Coulomb about 1773 (Holtz, 1969). He recognized the importance of cohesion and friction in the analysis of stability problems.

The science of soil mechanics is generally attributed to the late Karl Terzaghi, who pioneered important research, initiated laboratory tests to demonstrate soil behavior, and first applied the term "soil mechanics" to the field of study (Holtz, 1969).

In a relatively short period of time, tremendous amount of research in testing techniques, field evaluations, and analytical procedures have been developed. Proctor, Atterburg, and Casagrande are but few of the men who have contributed greatly to this science. They have accumulated detailed and accurate information on the physical characteristics and properties, and on the pattern of behavior under the varied conditions encountered in practice (Burmister, 1948).

Soil mechanics has become an indispensable tool to the planner and designer and as an aid to the builder who works with soil. However, soil mechanics has not yet reached the point where full confidence can be placed on theoretical analysis; in fact, there are some areas where no workable analysis is available (Soil Survey Staff, 1966). This is especially true of tropical soils. Very little reliable information about the engineering properties of tropical soil is available in the literature. This paucity of information is due to the general lack of engineering studies of these soils (Pearing, 1968).

As far back as 1915, Kelley stated that the normal methods of classification usually employed in temperate soils are not adaptable to Hawaiian conditions. Today, we realize more than ever that this statement made more than 56 years ago should be heeded by soil scientists and engineers who work with tropical soils. Even with all kinds of chemical, physical and mineralogical data in our possession, no serious attempts have been made to systematically interpret them so that they may be used advantageously for engineering design. This deficiency is due to the fact that many of us still treat tropical soils like temperate zone soils.

The soils of Hawaii have been mapped and classified, and much chemical, physical, and mineralogical data have been collected. These data are being used primarily to interpret soils for agricultural production. There is now a need for more urban and recreational development. The impact of urbanization and the competition for land has necessitated the need for accurate interpretations of soils for engineering uses.

Planners should know the location and extent of soils that are subject to flooding; the soils that have low bearing capacity; the soils with high shrink-swell properties; and the soils with potential slide hazards. Some of these facts about soils can be learned from soil maps. One major objective of soil survey is the prediction of soil behavior under defined use and management. In agriculture, the ultimate objective of soil science is to predict the yield and quality of specific crops under defined management.

The application of knowledge gained in the selection of soils for agricultural purposes is tantamount to the selection of soils as foundation material for housing, roads and streets, septic tanks, golf courses, and for many other non-agricultural uses. Predictions must be made prior to construction as to how soil will perform. Land should be zoned so that houses are not allowed to be built where there is imminence of flood, soil creep or cracking and settling of foundations.

One of the most widely used engineering soil classification systems is the Unified system developed by Casagrande and modified by the Bureau of Reclamation and the Corps of Engineers. This classification system categorizes soils into groups with respect to their behavior as engineering material. Long experience with use of Hawaiian soils as foundation material for small structures suggests that the Unified classification system does not satisfactorily predict soil behavior in Hawaii.

For example, soils categorized as MH soils under the Unified classification system are considered poor foundation material. Figure 1 illustrates that Hawaiian soils in the MH group are generally used for foundations with good results. Figure 2 depicts the stability of these soils when they are used as unlined irrigation ditches, and Figure 3 shows how steep cuts along highways resist erosion even when devoid of vegetation.

A more extreme example of the inadequacy of the Unified classification system for Hawaiian soils is shown in Figures 4 and 5. These houses rest on a soil classified in the OH group. Such soils are considered to have very poor bearing value for foundations (F.H.A., 1959) and yet small structures have been built on such soils for many years with no recorded foundation failure.

While the Unified classification system incorrectly predicts Hawaiian soil behavior, in many cases it does apply. It does so in soils classified in the CH group. CH soils are generally considered unsuitable for foundations. Because of the general inapplicability of the system in Hawaii, engineers have tended to disregard this system entirely. Figure 6 illustrates a consequence of this error.

The objectives of this investigation are:

1. To classify some of the Hawaiian soils by both the American Association of Highways Officials System and the Unified Soil Classification System.
2. To arrive at a rational explanation for the differences in engineering properties between tropical and temperate soils.

Figure 1. — Housing Development on MH Soils on Oahu, Hawaii

Figure 2. -- Unlined Irrigation Ditch on MH Soil Showing Stable Side Slopes

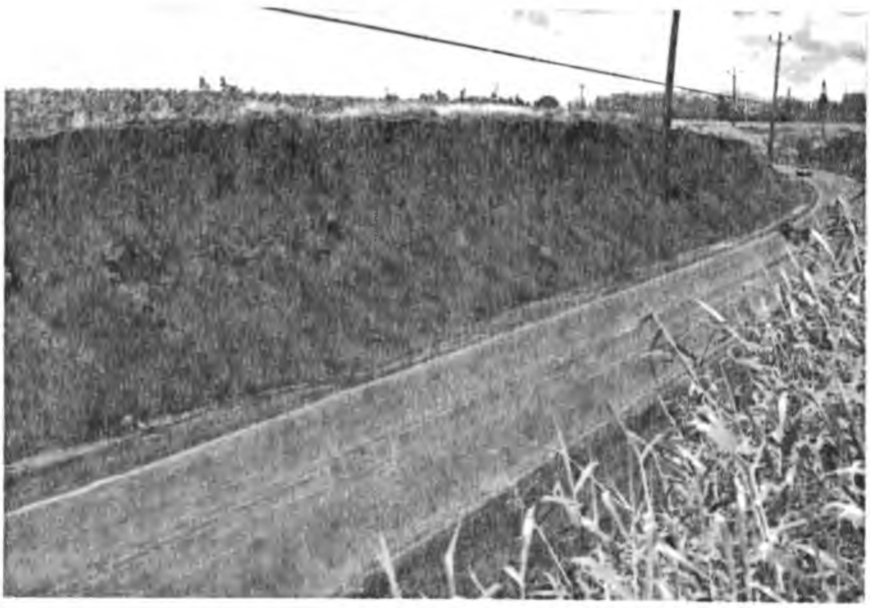


Figure 3. — Steep Road Cuts on MH Soils Having Stable Slopes

Figure 4. — House Built on OH Soil in Pepeekeo, Hawaii

Figure 5. -- House on Deep OH Soil in Hilo, Hawaii

Figure 6. -- Houses Built on Steep Slopes on Soils with Montmorillonite Mineralogy

3. To interpret the soil classification so that they can be used to predict the performance of the soils as construction material for roads and as foundation material for dams and dwellings.

REVIEW OF LITERATURE

Classification is an arrangement of objects into classes or groups. Classification is not static but often changes as knowledge expands. The best classification is one which can best serve the purpose for which it was made (Soil Survey Staff, 1962). Soils may be classified in many ways and several classification systems have been developed (Soil Survey Staff, 1960 and 1970; Casagrande, 1948; AASHO, 1966). The various classification systems used in soil mechanics are discussed by Casagrande (1948). The two most widely used classification systems in soil mechanics are the American Association of State Highway Officials (AASHO) and the Unified Soil Classification Systems.

AASHO CLASSIFICATION SYSTEM

The American Association of State Highway Officials System (AASHO, 1966), a system of classifying engineering properties of soils based on field performance of highways, was previously referred to as the Public Roads Administration soil classification system because it was developed by that organization in 1931. This system was revised by a subcommittee of the Highway Research Board in 1945, and it became the standard of AASHO since that time.

The grouping of soils of about the same general load-carrying capacity and service resulted in seven basic groups that were designated A-1 through A-7. The best soils for road subgrades were classified as A-1, the next as A-2, etc., with the poorest soils being classified as A-7. The seven basic soil groups have been divided into subgroups with a group index to approximate within group variations. The classification is made by using the test limits and group index values shown in Table 1.

Table 1. -- Classification of Soils in the AASHO System*

General Classification	Granular Materials (35% or less passing No. 200)							Silt-Clay Materials (More than 35% passing No. 200)			
Group Classification	A-1			A-2							A-7
	A-1-a	A-1-b	A-3	A-2-4	A-2-5	A-2-6	A-2-7	A-4	A-5	A-6	A-7-5 A-7-6
Sieve Analysis, Percent passing:											
No. 10	50 max.	--	--	--	--	--	--	--	--	--	--
No. 40	30 max.	50 max.	51 min.	--	--	--	--	--	--	--	--
No. 200	15 max.	25 max.	10 max.	35 max.	35 max.	35 max.	35 max.	36 min.	36 min.	36 min.	36 min.
Characteristics of Fraction passing No. 40:											
Liquid limit	--		--	40 max.	41 min.	40 max.	41 min.	40 max.	41 min.	40 max.	41 min.
Plasticity index	6 max.		N.P.	10 max.	10 max.	11 min.	11 min.	10 max.	10 max.	11 min.	11 min.
Usual Types of Significant Constituent Materials	Stone Fragments, Gravel and Sand		Fine Sand	Silty or Clayey Gravel and Sand				Silty Soils		Clayey Soils	
General Rating as Subgrade	Excellent to Good							Fair to Poor			

*From AASHO Designation: M 145-66 I.

UNIFIED SOIL CLASSIFICATION SYSTEM

The Unified Soil Classification System is based on the system developed by Casagrande (1948) of Harvard University for the Corps of Engineers during World War II. Since then, the original classification has been expanded and revised in cooperation with the U.S. Bureau of Reclamation and the Corps of Engineers (Corps of Engineers, 1953; U.S. Department of Interior, 1960).

The Unified Soil Classification System identifies soils according to their texture and plastic qualities and grouped with respect to their performances as engineering construction material. The symbols used are connotative of the soil makeup. In this system, soil materials are identified as coarse grained (G or S), fine grained (M or C), and highly organic (O). For example, soils that consist primarily of fine-grained, either plastic or non-plastic material, are identified by the symbols ML or CL if the liquid limit is low and by MH or CH if the liquid limit is high. If the classification is borderline between two groups, the symbols for both groups are given, joined by a hyphen. An example of such a borderline classification is "ML-CL" (U.S. Department of Interior, 1960). The A-line is represented by the equation:

Plasticity index = 0.73 x (liquid limit -20)

It represents the boundary between inorganic clays (C groups) which occur above the A-line and the inorganic silts and clays (M groups) which occur below. Soils with liquid limits of less than 50 percent are placed in the L group and those with liquid limits of more than 50 percent are placed in the H group.

These two classification systems together with the USDA system are compared in Table 2 (Soil Survey Staff, 1970). Much has been written about these classification systems, and tables have been developed to predict the performance of soils as construction material for roads and as foundation material for dams and homes. Haine and Hill, (1948) and Casagrande, (1948) state that after a soil is properly classified, it is possible to indicate the engineering properties typical of the various soil groups and their use in engineering structures. Soils of Hawaii, however, do not behave as temperate climate soils, and these criteria are useless in predicting the behavior of engineering properties of tropical soils (Townsend et al., 1969).

To correct this difference in behavior between temperate and tropical soils, Vallerga and van Til (1970) devised a classification system for lateritic soils in Thailand by extending the Unified Soil Classification System to include symbols for defining the durability characteristics of gravel and sand aggregate particles and the degree of plasticity of the fine grained materials in the gravel and sand. They included an intermediate group I to cover part of the L range because the suffixes L and H in the original system are inadequate to distinguish the entire range of compressibility.

Vargas (1948) suggested that the two major divisions of fine grained soils be divided into subgroups according to mineralogical composition and organic matter content. He suggested that a kaolin group be added. If a new group for the kaolin type clays is added, this would introduce subgroups of kaolin type clays, KH or KL, which is common in Hawaiian soils.

Table 2. -- General Relationship of Systems Used for Classifying Soil Samples*

USDA Texture Class & Symbol	Unified Symbol	AASHO Symbol	Soil Properties Related to Classification
Clay; silty clay "c"; "sic"	CH	A-7	High shrink-swell clays
	MH	A-7	Mica, iron oxide, kaolinitic clays
	CL	A-7	Low LL. Generally clay <45%
Silty, clay loam "sicl"	CL	A-7	Low LL. Plastic. (A-6 clay <30%)
	ML-CL	A-7	Low LL. Mod. Plastic. (A-6 clay<30%)
	CH	A-7	High LL. High shrink-swell clays
	MH	A-7	High LL. Mica, iron oxide, kaolinitic
Clay loam "cl"	CL	A-6 or A-7	Low LL. Plastic
	ML-CL	A-6	Low LL. Moderately plastic
	CH	A-7	High LL. High shrink-swell clays
	MH	A-7	High LL. Mica, iron oxide, kaolinitic
Loam "l"	ML-CL	A-4	Moderately plastic (A-6 clay > 21%)
	CL	A-6	Plastic (A-4 clay < 22%)
	ML	A-4	Low plasticity. (A-7 clay > 21%)
Silt loam "sil"	ML-CL	A-4	Moderately plastic. (A-6 clay > 21%)
	ML	A-4	Low plasticity. (A-7 clay > 21%)
	CL	A-6	Plastic
Silt - "si"	ML	A-4	Low plasticity
Sandy clay "sc"	CL	A-7	Over 50% fines
	SC	A-7	50% or less fines
Sandy clay loam "scl"	SC	A-6	Plastic. 36 to 50% fines
	SC	A-2-6	Plastic. 35% or less fines
	SM-SC	A-6	Plastic. Over 50% fines
Sandy loam "sl"	SM	A-2-4	Low plasticity
	SC	A-2-4	Plastic
	SM-SC	A-2-4	Moderately plastic
Fine sandy loam "fsl"	SM	A-4	Nonplastic. 50% or less fines
	ML	A-4	Nonplastic. Over 50% fines
	ML-CL	A-4	Moderately plastic. Over 50% fines
	SM-SC	A-4	Moderately plastic. 50% or less fines
V.F. sandy loam "vfsl"	ML-CL	A-4	Moderately plastic
	ML	A-4	Low plasticity
Loamy sands "ls"; "lfs" "lvfs"	SM	A-2-4	Nonplastic. 35% or less fines
	SM-SC	A-2-4	Moderately plastic. 35% or less fines
	SM	A-4	Low plasticity. Over 35% fines
	ML	A-4	Little or no plasticity
Sand; fine sand "s"; "fs"	SP-SM	A-3	5 to 10% fines (approx.)
	SM	A-2-4	Over 10% fines (approx.)
	SP	A-3	Less than 5% fines
V.F. sand - "vfs"	SM	A-2-4	Low plasticity
	ML	A-4	Little or no plasticity
Coarse sand "cs"	SP;GW	A-1	Less than 5% fines
	SP-SM	A-1	5 to 12% fines
	SM	A-1	13 to 25% fines
	SM	A-2-4	Over 25% fines
Gravel "G" 50% pass #200 50% of coarse pass #4 sieve	GP;GW	A-1	Less than 5% fines
	GM or GC	A-1	5 to 25% fines
	GM or GC	A-2	26 to 35% fines
	GM	A-4	Over 35% fines
	GC	A-6	Over 35% fines

*From Basic Soil Mechanics--Soil Conservation Service, 1966.

Casagrande (1948) suggested that in localities where kaolin type clays are important, it would be desirable to add separate subgroups for KL, KI and KH. He further suggested that a division be made for liquid limit ranging below 35 and those from 35 to 50. The soils in such an intermediate group were to be identified with the letter I as shown in Table 3.

INDEX PROPERTIES

Certain soil tests such as gradation, liquid limit, and plastic limit are used to assist in the classification of a soil (PCA Primer, 1962).

Index properties are used to classify soils into broad groups to predict certain behaviors. This is distinguished from engineering properties where design values are obtained.

Gradation. The gradation of soils is one of the most important properties used in classifying soils. There are two procedures commonly used by engineers to determine grain size distribution: (a) sieve analysis and (b) hydrometer method. The analysis that should be used depends upon the soil in question. If the grain size distribution is great enough, both analyses must be used. For most tropical soils, gradation is not reliable. The soils usually are cohesive with very little coarse material. The clays are difficult to disperse and have a tendency to form stable aggregates (Chotimon, 1969). The amount of clay in these soils can be estimated by multiplying the 15-bar water content by a factor of 2.5 (Soil Survey Staff, 1960).

Atterburg Limits (Liquid Limit and Plasticity Index). Atterburg devised tests to determine the moisture content of a soil when it changes

Table 3. -- Suggested Expansion of Unified Groups for Fine-Grained Soils*

<table>
<tr><th>Original Group</th><th colspan="2">Suggested Expansion</th></tr>
<tr><td rowspan="2">CL
ML
OL</td><td>CL
KL
ML
OL</td><td>LIQUID LIMIT = 35%</td></tr>
<tr><td>CI
KI
MI
OI</td><td>LIQUID LIMIT = 50%</td></tr>
<tr><td>CH
MH
OH</td><td>CH
KH
MH
OH</td><td></td></tr>
</table>

*From Casagrande, 1948.

from one major physical condition to another. They show the water-holding capacity of soils under various conditions. The four states of consistency utilised are the liquid, plastic, semi-solid, and solid states. The moisture content at which the soil changes from the liquid state to the plastic state is called the liquid limit. This test is really an index of cohesion as cohesion retards flow. Sandy soils have low liquid limits and silts and clays have high liquid limits. Liquid limits increase as fineness increases and load-carrying capacity decreases.

Plastic limit is the moisture content at which the soil ceases to behave plastically and the soil tends to crumble when deformed. The plastic limit is governed by the clay content. Load-carrying capacity increases as the moisture content decreases below the plastic limit.

The numerical difference in moisture content between the liquid limit and plastic limit is called the plastic index. The plasticity index is an important soil characteristic because it is a measure of the plastic behavior of soils and a general indicator of the shrink-swell potential. The plasticity index gives the range in moisture content at which a soil is in a plastic state. When the liquid limit or plastic limit cannot be determined or when the plastic liquid is equal to or higher than the liquid limit, the plastic index is reported as nonplastic (NP) (PCA Soil Primer, 1962).

The Atterburg limits have been used extensively and quite successfully to classify soils in temperate regions and, in a general way, to predict their behavior on the basis of these index properties. However, correlation of this nature with tropical soils can lead to erroneous conclusions (Townsend et al., 1969).

Flach* observed that a simple linear regression equation showing the relationship between liquid limit and percent clay could be used to obtain a rough estimate of liquid limit. The equation for clays with good dispersion:

$$\text{Liquid Limit} = (0.9 \times \%\ \text{clay}) + 10$$

Many soils are difficult to disperse. For these soils, the percentage of clay is determined by the higher value of (1) the measured clay content, or (2) 2.5 x the percentage of water retained by 15-bar tension. The equation to estimate the liquid limit for these soils:

$$\text{Liquid Limit} = (2 \times 15\text{-bar water}) + 10$$

In one of their studies, the Corps of Engineers (1951) found that a correlation coefficient of 0.882 was obtained for a line of regression represented by the equation:

$$\text{Liquid Limit} = 0.97\ (\text{percent clay}) + 15.3$$

(with a standard arror of 10.5).

PROCTOR COMPACTION TEST

The Proctor compaction test (Proctor, 1943) commonly referred to as maximum dry density and optimum moisture, has been used extensively by the engineering profession. Realising that the use of soil-moisture content that obtains the least voids with a particular method of compaction results in the most watertight and stable dams, Proctor (1943) devised a procedure in the engineering control of earth dams and construction. The required soil density is obtained by controlling the

*Statement to the author by K. Flach, Soil Survey Laboratory, Riverside, California.

correct moisture content in the soil before it is compacted.

A particular soil may be compacted to many different densities due to the variation in water content. Therefore, the highest extent to which the voids are reduced by compaction at that moisture content is referred to as maximum density and optimum moisture.

Moisture-density data can be helpful in predicting many characteristics of in-place soils, but such data should be regarded as an indicator only and should not be used as the basis for design.

Several factors influence the density obtained by compaction. The important ones are: (1) the moisture content of the soil (2) the nature of the soil, its gradation and physical properties and (3) the type and amount of compactive effort (PCA Primer, 1962).

Dry Density: Dry density of a soil is a very important indicator property because most of the mechanical properties of a soil relate in part to density. Generally speaking, for a particular type of soil, strength increases, while compressibility, permeability, and shrinkage potential decreases as dry density increases (Soil Survey Staff, 1966).

For soils with a high moisture content, the Hawaii State Highway Division performs the test by air drying the soil in increments from the natural state and by determining the density at each increment. This method of analysis gives a curve which is more indicative of the behavior under natural conditions because dehydration of the soil is not possible in the field (Tateishi, 1967). This procedure is important as these Hydrandepts dehydrate irreversibly into sand and gravel size fragments and would not give a true indication of its proper texture, properties and behavior in the field.

Optimum Moisture: The engineering behavior of a soil is very closely related with some interaction between the solid portion of the soil and the moisture in it. The effect of the moisture content of a soil upon the density is the most important principle of soil compaction.

The influence of moisture content on the density of a soil is illustrated by the use of percent moisture content versus maximum dry density curve. This curve is unique for a particular soil and compaction method, and there is an optimum moisture content at which a given soil can be compacted to the greatest density. The shrink-swell potential, ease of compaction, and strength vary with moisture content.

Kawano and Holmes (1958) studied the factors that influenced soil compaction of Hawaiian soils. A highly significant correlation coefficient was obtained when optimum moisture was correlated with plastic limit or with liquid limit. From data available, Hawaiian soils at a given dry density has a higher optimum moisture content than continental U.S. soils.

MINERALOGY: The engineering properties are influenced mostly by the soil type, its gradation, and the composition (PCA Primer, 1962). Many of the physical properties of a clay system are affected by its particle size distribution. Some of the properties are bulk density, specific surface, water-holding capacity, permeability, shrink-swell potential and strength. It is safe to say that these factors are related ultimately to mineralogical composition (Low, 1968).

Generally, tropical soils have a granular structure due to the high content of iron and aluminum oxides. The presence of iron in tropical soils is one of the most important factors responsible for desirable engineering properties (Winterkorn, 1968). The clays are characterized by a high content of iron and aluminum silicates and low silica content. The properties sometimes differ greatly from the clays in temperate regions (Kelley, 1915).

Maslov (1950) a Russian scientist, considered that each mineral particle is completely surrounded by a membrane of bound water. Denisov (1950) stated "...that cohesion of clay particles may be due to the influence of molecular attraction between particles (including colloids) as well as to cementation by different chemical compounds."

There is unpublished evidence at the University of Hawaii that cementation by amorphous coatings around soil particles render Hawaiian soils more stable than soils of equivalent plastic indexes of other areas.

MATERIALS AND METHODS

SOILS

Engineers are mainly interested in the subsoil or C horizon in characterizing and determining properties of soils. The data of subsoils of 55 soil series were, therefore, examined. The data represents the analysis of only one sample in a few cases but may represent as many as 75 or more samples of the same series in other cases. In the latter, the data were averaged for each series. The data and classification of soils are presented in Table 4. The description of each series is available in any office of the Soil Conservation Service in Hawaii.

METHODS

The data for liquid limit, plastic limit, plastic index, dry density, and optimum moisture were obtained from various agencies. The data for specific gravity, 15-bar water, mineralogy, and organic carbon were obtained from the soil data bank at the University of Hawaii. The methods described below are among those used in previous research from which most of the data for this report were collected.

1. Liquid Limit:

The soil used for this test was material passing through a No. 40 sieve. Distilled water was added to the soil until a fairly stiff paste consistency was obtained. A pet of soil paste was then placed in the cup of the liquid limit apparatus and a groove was made in the paste with a grooving tool through the soil across the center of the soil mass. The moisture content at which 25 blows or drops of the cup closed the groove along a length of one-half inch was determined to be the liquid limit. A standard drop of 1 cm was used (ASTM Designation: D423).

[illegible] Classification [illegible] Soils [illegible] in this Investigation

No.	Soil Series	Classification: New Classification	Classification: USDA	Classification: Unified	Classification: AASHO	Atterburg Limit: LL	Atterburg Limit: PI	Density Lbs/Ft^3	Optimum Moisture	Unconfined Compression Lbs/Ft^2	Specific Gravity	Mineralogy	Organic Carbon
1	Akaka	Typic Hydrandepts	Sicl	OH	A-7-6	290	107	--	--	--	--	Thixotropic	6.57
2	Alaeloa	Orthoxic Tropohumults	Sic	MH	A-7-5	64	21	95	31	10,648	--	Oxidic	--
3	Ewa	Aridic Haplustolls	Sicl	CL	A-7-6	44	20	104	24	--	2.97	Kaolinitic	--
4	Haiku	Humoxic Tropohumults	C	ML	A-4	40	6	--	--	--	--	Ferritic	--
5	Halawa	Orthoxic Tropohumults	Sic	ML	A-4	39	7	--	--	--	--	Oxidic	--
6	Haleiwa	Typic Haplustolls	Sic	MH	A-7-5	68	34	--	--	--	--	Mixed	--
7	Halii	Typic Gibbsihumox	Sicl	ML	A-5	41	N.P.	--	--	--	--	Ferritic	--
8	Kalihmaile	Ustoxic Humitropepts	Sic	ML	A-7-5	44	15	100	27	--	2.99	Kaolinitic	--
9	Hamakuapoko	Orthoxic Tropohumults	Sic	--	--	--	--	82	37	--	--	Oxidic	--
10	Hanalei	Typic Tropaquepts	Sic	MH	A-7-5	69	23	91	30	2,300	2.81	Mixed	1.46
11	Hanamaulu	Oxic Humitropepts	Sic	MH-ML	A-7-5	50	18	95	30	--	2.97	Oxidic	--
12	Hanipoe	Typic Dystrandepts	Sil	MH	A-5	110	9	--	--	--	--	Medial	--
13	Hilo	Typic Hydrandepts	Sicl	OH	A-7-6	152	47	--	--	--	--	Thixotropic	3.23
14	Honokaa	Typic Hydrandepts	Sicl	OH	A-7-6	136	38	--	--	--	--	Thixotropic	7.80
15	Honouliuli	Typic Chromusterts	C	CL	A-7-6	47	24	109	22	--	2.98	Halloysitic	.23
16	Kahana	Tropeptic Haplustox	Sic	ML	A-7-5	43	16	99	27	--	2.94	Kaolinitic	--
17	Kaneohe	Humoxic Tropohumults	Sic	MH	A-7-5	64	15	91	31	7,791	2.89	Oxidic	--
18	Kapaa	Typic Gibbsihumox	Sic	MH	A-7-6	110	53	--	--	--	--	Gibbsitic	.98
19	Kawaihapai	Cumulic Haplustolls	Cl	CL	A-6	40	19	114	20	--	--	Mixed	--
20	Keahua	Typic Torrox	Sicl	ML	A-7-5	43	16	104	24	--	2.95	Kaolinitic	.45
21	Kekaha	Cumulic Haplustolls	Sic	MH	A-7-5	68	31	--	--	--	--	Mixed	1.33
22	Kemoo	Oxic Rhodustalfs	Sic	MH	A-7-5	68	33	93	31	--	--	Oxidic	--
23	Kikoni	Typic Eutrandepts	Vfsl	MH	A-7-5	123	13	--	--	--	2.62	Medial	--
24	Kohala	Ustic Humitropepts	Sic	MH	A-7-5	59	24	87	35	--	--	Kaolinitic	.97
25	Kolekole	Ustoxic Humitropepts	Sicl	ML	A-5	43	10	94	33	--	2.97	Oxidic	--
26	Koloa	Tropeptic Eutrorthox	Sic	MH	A-7-5	50	19	99	28	--	3.08	Kaolinitic	--
27	Kukaiau	Hydric Dystrandepts	Sicl	MH	A-7-5	143	31	--	--	--	--	Thixotropic	--
28	Kunia	Ustoxic Humitropepts	Sic	MH	A-7-5	51	21	98	28	--	2.93	Kaolinitic	--
29	Lahaina	Typic Torrox	Sic	ML	A-7-6	44	17	98	26	12,452	2.84	Kaolinitic	--
30	Leilehua	Humoxic Tropohumults	Sic	MH	A-7-5	59	28	95	30	--	2.95	Oxidic	.84
31	Lihue	Tropeptic Eutrorthox	Sic	MH	A-7-5	54	20	97	29	--	3.02	Kaolinitic	.45
32	Lolekaa	Humoxic Tropohumults	Sic	MH	A-7-5	67	19	89	30	--	--	Oxidic	.67
33	Lualualei	Typic Chromusterts	C	CH	A-7-6	67	44	104	25	--	3.03	Montmorillonite	.21
34	Mahana	Oxic Dystrandepts	Sicl	MH	A-7-5	54	15	99	29	--	--	Medial	.27
35	Maile	Hydric Dystrandepts	Sic	OH	A-7-6	222	41	--	--	--	2.66	Thixotropic	10.04
36	Makaweli	Typic Torrox	Sicl	--	--	--	--	101	27	--	3.19	Kaolinitic	.49
37	Mamala	Lithic Haplustolls	Sicl	CL	A-7-6	45	21	104	24	--	2.97	Kaolinitic	.64
38	Manana	Orthoxic Tropohumults	Sicl	MH	A-7-5	56	16	--	--	--	--	Oxidic	--
39	Mokuleia	Entic Haplustolls	Cl	--	--	--	--	106	24	--	--	Carbonatic	--
40	Molokai	Typic Torrox	Sicl	ML	A-7-6	44	17	98	26	--	2.94	Kaolinitic	.46
41	Naalehu	Typic Eutrandepts	Sil	MH	A-7-5	71	19	--	--	--	2.91	Medial	.90
42	Nohili	Cumulic Haplaquolls	C	CH	A-7-6	108	67	--	--	--	--	Carbonatic	.80
43	Paaiki	Typic Dystrandepts	Sic	MH	A-7-5	72	24	--	--	--	--	Medial	--
44	Paaloa	Humoxic Tropohumults	Sic	ML-MH	A-7-5	50	11	--	--	--	--	Oxidic	.75
45	Pala	Typic Haplustolls	C	MH	A-7-5	56	22	--	--	--	2.92	Kaolinitic	.21
46	Pane	Typic Dystrandepts	L	ML	A-7-5	43	11	--	--	--	--	Medial	2.57
47	Pauwela	Humoxic Tropohumults	C	ML	A-4	39	8	--	--	--	--	Ferritic	1.68
48	Puhi	Typic Umbriorthox	Sicl	MH	A-7-5	63	24	94	33	--	2.97	Oxidic	1.25
49	Pulehu	Cumulic Haplustolls	Fsl	MH	A-7-5	67	35	105	23	--	2.99	Mixed	--
50	Wahiawa	Tropeptic Eutrustox	Sic	MH	A-7-5	57	22	91	29	9,342	2.89	Kaolinitic	--
51	Waiakoa	Aridic Haplustolls	Sicl	CL	A-7-5	35	12	--	--	--	--	Kaolinitic	.53
52	Waialua	Typic Haplustolls	Sic	MH	A-7-5	64	32	96	29	--	2.91	Kaolinitic	--
53	Waikaloa	Ustollic Eutrandepts	Sicl	MH	A-7-5	68	27	--	--	--	--	Medial	1.02
54	Waikane	Typic Torrox	Sic	MH	A-7-5	74	25	89	28	5,548	2.94	Kaolinitic	--
55	Waipahu	Torretic Haplustolls	Sic	ML	A-7-6	43	17	98	25	12,328	2.75	Kaolinitic	--

2. Plastic Limit:

The plastic limit test consisted of rolling out a ball of moist soil on a smooth surface such as a plate of glass to form a thread. The moisture content at which the thread crumbled into small cylindrical pieces of about one-half inch length with a diameter of one-eighth inch was determined to be the plastic limit. These pieces of soil were placed in a moisture can, weighed before and after being oven dried at 105° C, and the moisture percentage was calculated on an oven dry weight basis (ASTM Designation: D424).

3. Plastic Index:

The numerical difference between the liquid limit and the plastic limit is called the plastic index.

4. Moisture-Density Relationship:

a. Modified Proctor

The relationship between the moisture content and density of soils when compacted was determined with a 10-pound rammer dropped from a height of 18 inches following the procedure given in ASTM Designation: D1557-66T, Method A. An adequate quantity of pulverized soil was passed through a No. 4 (4.76 mm) sieve and thoroughly mixed with water. A representative sample was then compacted in a 4-inch mold in 5 equal layers to give a total compacted depth of about 5 inches. Each layer was compacted by 25 uniformly distributed blows by the rammer dropping free from a height of 18 inches above the soil. A representative sample of the material was taken to determine the moisture content.

b. Standard Proctor

The standard proctor uses a 5.5 pound rammer dropped from a height of 10 inches. Otherwise, this procedure given in ASTM Designation: D698-66T is similar to the modified Proctor moisture density relationship test described above.

5. Specific Gravity:

The specific gravity of a soil is the ratio of the weight of the oven-dried soil to the weight of water displaced by the individual soil particles. This was determined by the use of a pycnometer to measure displacement of water by the soil as described by Wright (1934).

6. 15-Bar Water:

The moisture content retained at 15-bar was measured with the pressure membrane apparatus by following the procedure of Richards (1954).

7. Mineralogy and Particle Size:

According to the new soil classification system (Soil Survey Staff, 1970) the soils in Hawaii have oxidic, kaolinitic, montmorillonitic, halloysitic, or ferritic mineralogy. The mineralogy of these soils was determined by X-ray diffraction, chemical and differential thermal analyses. In cases where mineralogy does not apply in family differentiae, particle-size designations such as thixotropic and medial are used.

8. Organic Carbon:

Organic carbon was determined by the Walkley-Black (1934) method. The organic carbon in the air dried 100-mesh soil was oxidized in a potassium dichromate-sulfuric acid mixture, and the excess dichromate was back titrated with ferrous sulfate solution.

RESULTS AND DISCUSSION

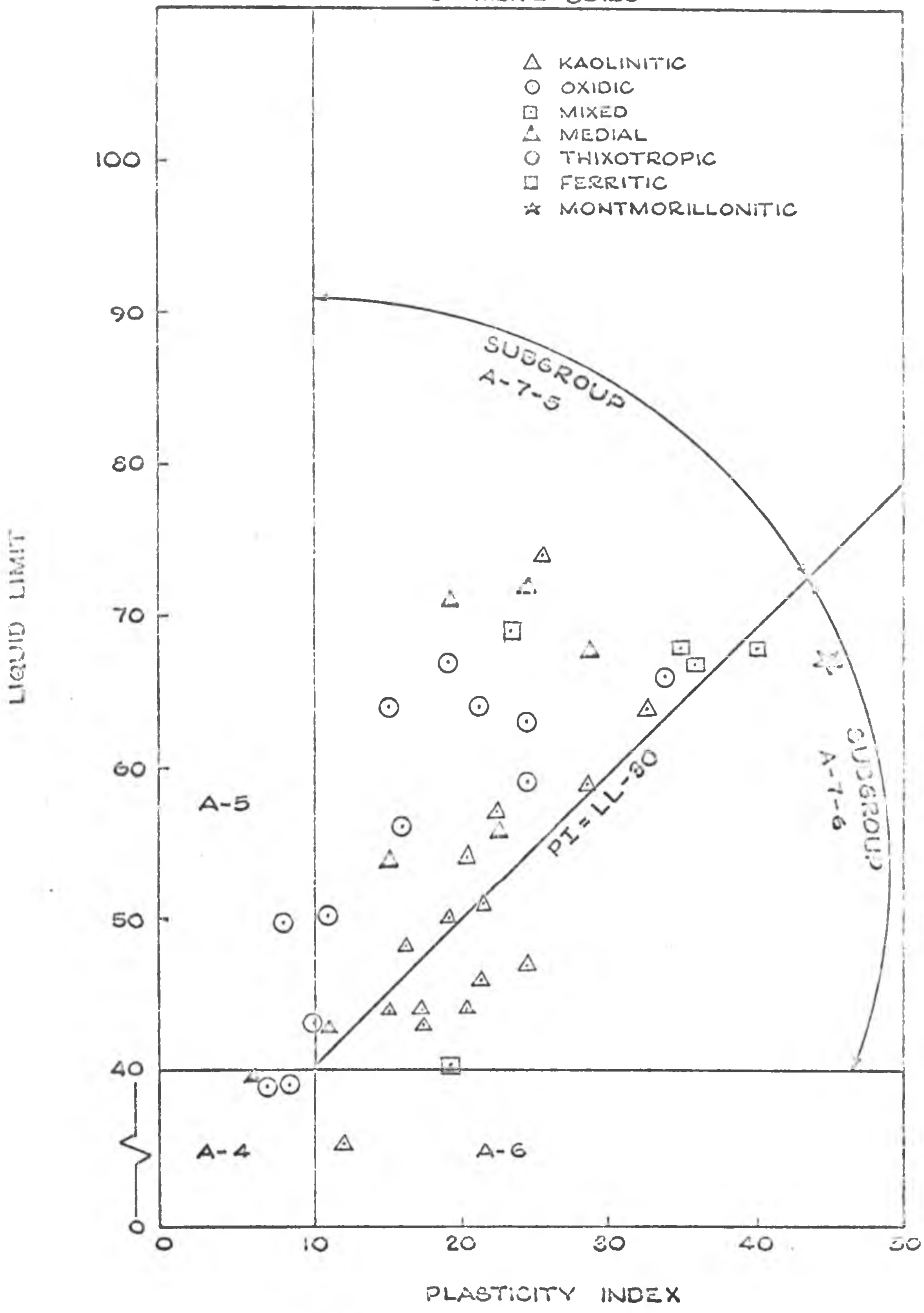
Engineering Soil Classifications

Soil mechanics data for 335 samples representing 55 soil series and 16 subgroups of the new Soil Taxonomy were gathered from various agencies in Hawaii. All these soils were considered cohesive soils or those in which more than 35 percent of the soil passed the No. 200 sieve. Procedure for these analyses may be found in the references cited in the following sections. Since only a few of the Hawaiian soils are coarse textured, none of these were considered. These samples were classified in both the AASHO and the Unified soil classification systems discussed below.

AASHO Classification: This system classifies soils into seven groups; these in turn were subdivided into 12 subgroups. Soils used in this study were classified in the AASHO system using the procedure described in AASHO Designation: M 145-66T. It is primarily based on laboratory determinations of particle-size distribution, liquid limit, and plasticity index as shown in Table 1.

The liquid limits and plasticity indexes of 41 soil series were plotted as shown in Figure 7. These soils fall into five groups: there were three A-4's, two A-5's, one A-6, ten A-7-6's and twenty-five A-7-7's. The group index, which is useful in determining the relative quality of the soil material for use in embankments and subgrades, was not determined because sieve analyses were not available. All of these soils were rated as fair to poor subgrade material requiring an increased thickness of base coarse in order to furnish adequate support for traffic loads. Soils in A-5 and A-7 categories possess high

FIGURE 7. CLASSIFICATION OF THE AASHO SYSTEM USING THE LIQUID LIMIT AND PLASTICITY INDEX FOR COHESIVE SOILS



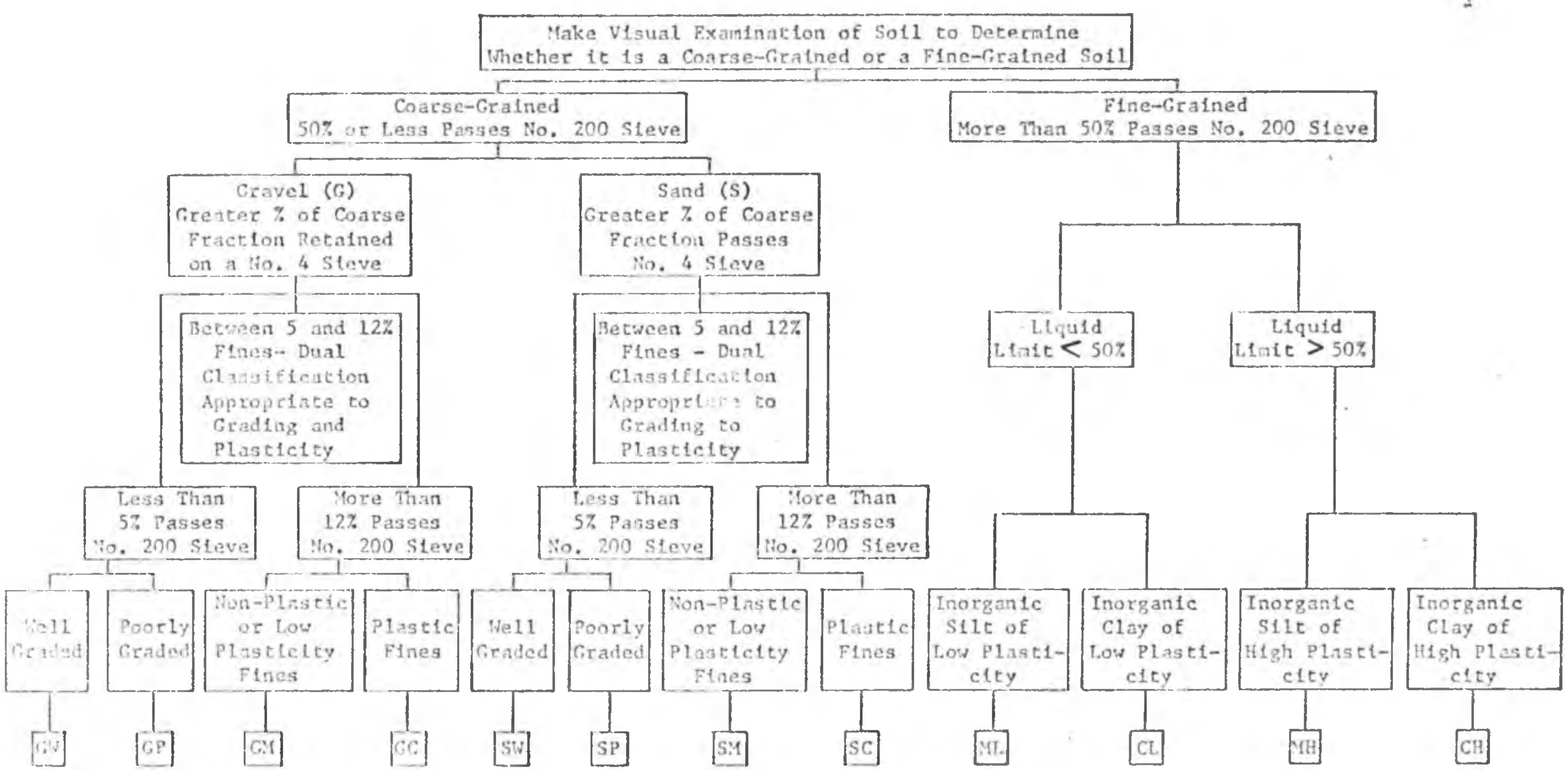
elasticity or compressibility (Lohnes and Handy, 1968) which is considered poor engineering soil material.

The AASHO classification is not used extensively in Hawaii because the system classifies Hawaiian soils into only a limited number of groups. Soils in these groups are rated as fair to poor subgrade material. Experience shows that this is not the case for many of these soils; for example, some of the soils in the Typic Torrox which are classified as A-7-6 have a maximum dry density of 97 to 101 pounds per cubic foot and an optimum moisture content of 24 to 26 percent. Unconfined compression of these soils run as high as 12,450 pounds per square foot. These results suggest that these soils are good subgrade material. There is sufficient practical evidence to indicate that the majority of Hawaiian soils, when classified in the AASHO system, fail to respond in the manner predicted by that classification. Therefore, some other classification must be used to predict the engineering behavior of Hawaiian soils.

Unified Soil Classification System: The samples were classified according to the Unified soil classification system given in ASTM Designation: D 2487-66T. The general procedure for classifying soils in the Unified soil classification is shown in Table 5. As previously stated, most of the soils in Hawaii are fine grained and are considered to be cohesive soils. The samples considered in this report were classified as ML, MH, CL, CH and OH; however, other soils in Hawaii do classify in the coarse textured groups as in Figure 8 showing houses built on SM soils.

Although the Hawaiian soils are distributed over a wide range of

Table 5. -- Field Procedure for Classifying Soils in the Unified System*



*From: Basic Soil Mechanics--Soil Conservation Service, 1966.

Figure 8. — Houses Built on Jaucus Series Which is Classified as an SM has Good Foundation Material

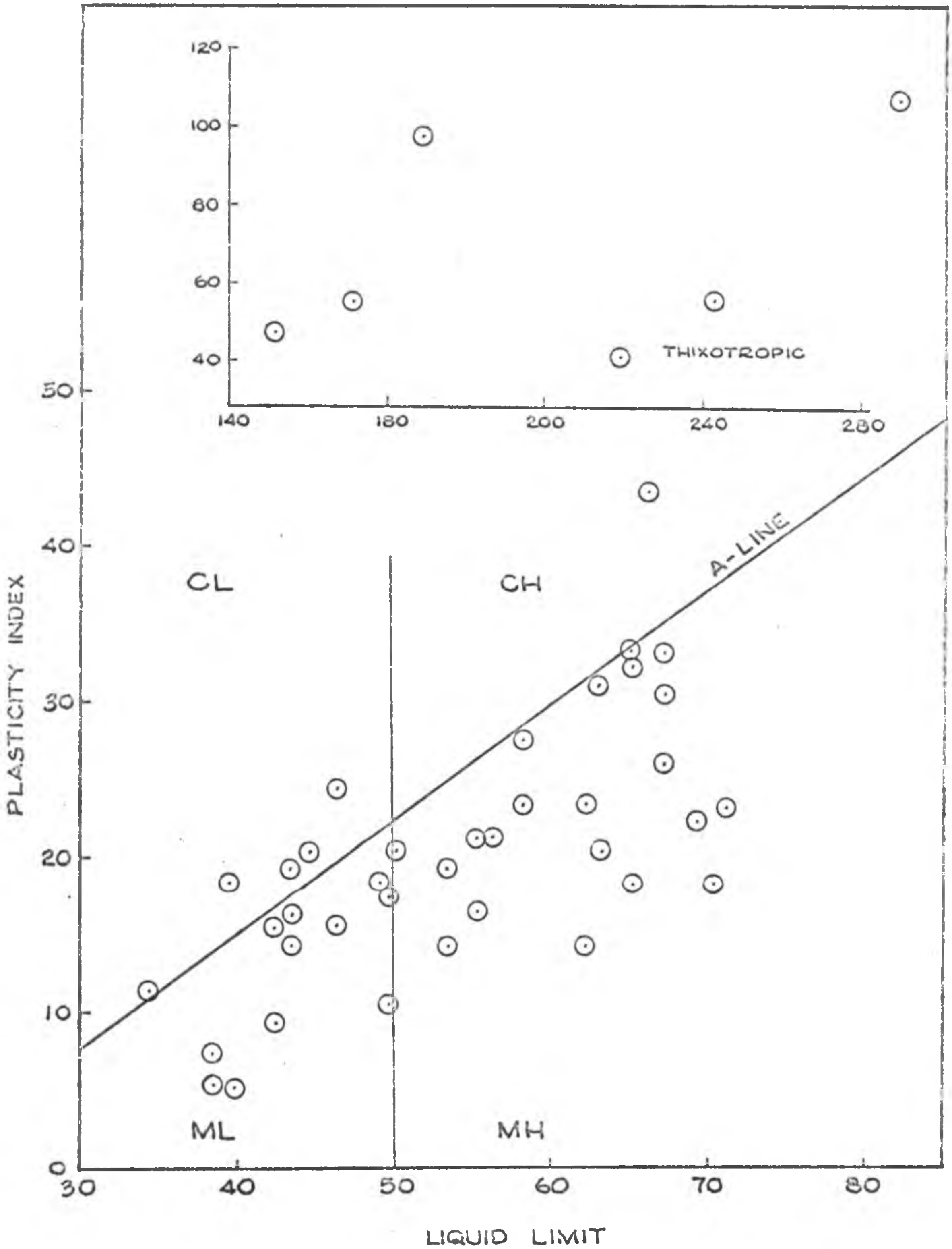
Unified soil groups, this classification system like the AASHO system has its limitations. Hawaiian soils respond differently from that of temperate regions when classified in the same group. In Figure 9, the Hawaiian soils are classified according to the Unified system.

CH Group--One soil was classified in this group. This was the Lualualei series, a very sticky and very plastic soil with montmorillonitic mineralogy. This soil was classified as Chromusterts in the new Soil Taxonomy. Lualualei soil was plotted above the A-line and had a plasticity index of 25 percent and a liquid limit of 67 percent. This was one group of Hawaiian soils which behaved in a manner predicted by the Unified classification system.

CL Group--The Ewa, Honouliuli, Kawaihapai, Mamala, and Waiakoa soils were classified in this group. With the exception of the Kawaihapai series which had mixed mineralogy, all of these soils had kaolinitic mineralogies. Apparent textures of these soils ranged from silty clay loam to clay. These soils were described as having slightly sticky to very sticky, and plastic to very plastic consistence. With the exception of the Honouliuli series, all others in this group were classified in the great group Haplustolls. The Honouliuli series were classified as Chromustarts, a soil similar to the Lualualei series except that it had liquid limits of less than 50 percent and a kaolinitic instead of a montmorillonitic mineralogy.

ML Group--The soils that fell into this group possessed ferritic, kaolinitic and oxidic mineralogies, and medial particle-size. Liquid limits for these soils ranged from 39 to 50 percent; the plasticity index ranged from 6 to 17 percent. Many Hawaiian soils fall into this

FIGURE 9. CLASSIFYING SOILS IN THE UNIFIED SOIL CLASSIFICATION SYSTEM ON THE PLASTICTY CHART



group.

MH Group—These soils were composed of kaolinitic and oxidic mineralogies and medial particle-size. The soils with medial particle-size generally had higher liquid limits. The liquid limits for other MH soils ranged from 50 to 70 percent; the plasticity index ranged from 11 to 53 percent. Again, this group contains a large portion of great groups in the Unified classification system.

OH Group—This group of soils includes the volcanic ash soils or Andepts that occur in the high rainfall areas. The high rainfall and dense vegetation account for the high organic matter content in these soils, thus differentiating this group from the MH group. All of the soils in this group had very high liquid limits ranging from 132 to about 290 percent. The plasticity indexes ranged from 21 to 107 percent but were generally about 40 percent. These soils are classified as Typic Hydrandepts or as Hydric Dystrandepts in the new Soil Taxonomy.

Relationship between Unified Soil Groups and Soil Taxonomy

The soils in the CL, CH, and OH groups are correlated to the great groups of the Soil Taxonomy. The other groups, however, did not correlate to any great groups.

Other great groups such as the Hydrandepts, Dystrandepts (Hydric), Tropofolists, and Troposaprists not included in this study will classify in the OH group.

Relationship between Atterburg Limits and Mineralogy Families

Mineralogy greatly influences the liquid limits and plastic limits of a soil, and they in turn are used to classify soils and to estimate soil properties. The montmorillonitic soils fall above the A-line; the kaolinitic group fell below the A-line; the oxidic group fell below the kaolinitic group; and the medial soils in turn fell below the oxidic group. The soils with thixotropic properties had extremely high Atterburg limits similar to OH (organic) soils. The above relationships are shown in Figure 10.

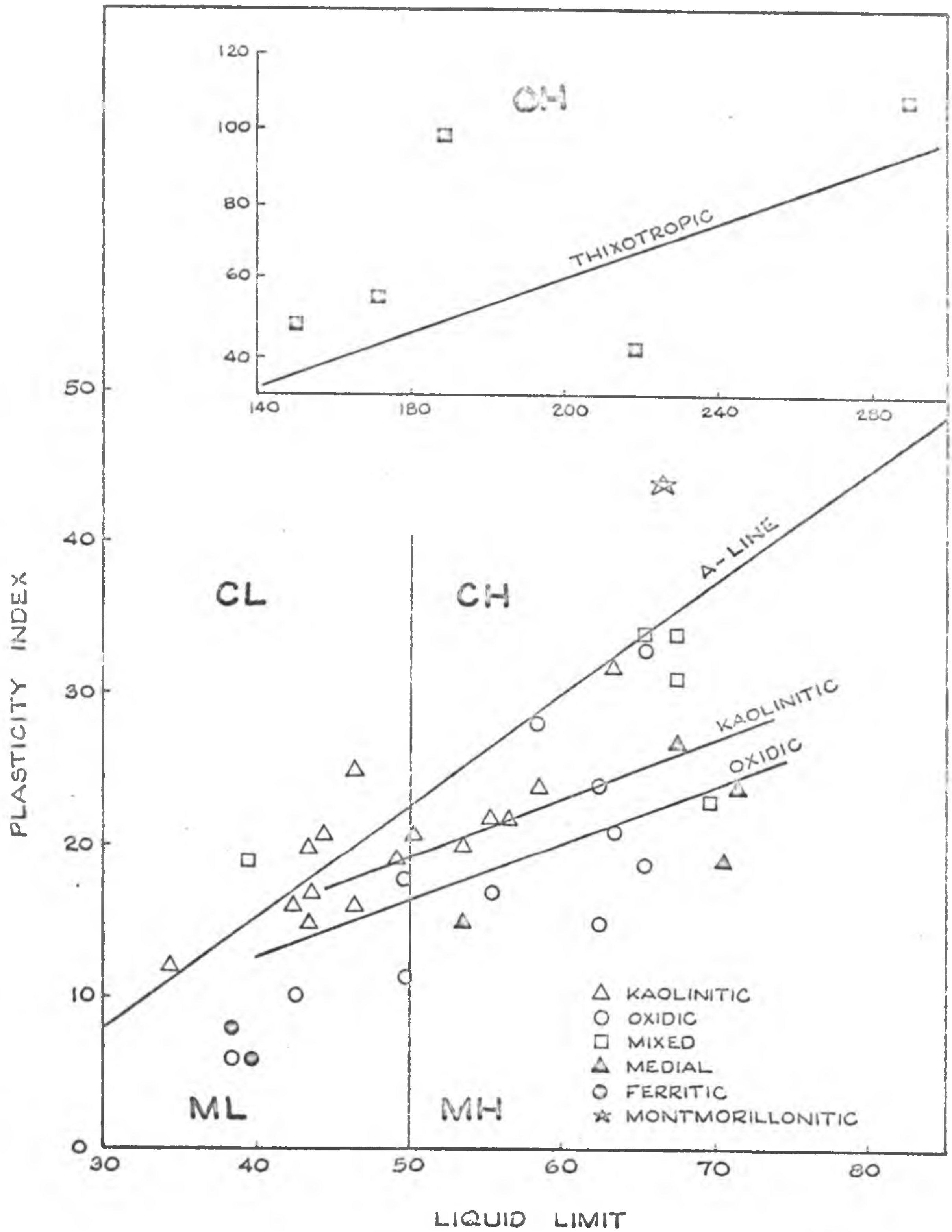
Montmorillonitic Family: The montmorillonitic family is defined as having more than 50 percent montmorillonite and nontronite by weight, or a mixture with more montmorillonite than any other single clay mineral (Soil Survey Staff, 1970). The soil with montmorillonitic mineralogy fell above the A-line and denoted high plasticity. This soil was described as being very plastic. The montmorillonitic soils of temperate areas and the tropical soils described by Bellerga and van Til (1970) would fall in the same general area on the plasticity chart. As expected, the montmorillonitic soil had a relatively high (67%) liquid limit.

The soil with montmorillonitic mineralogy was classified in the CH group.

Kaolonitic Family: A kaolinitic family is one with more than 50 percent kaolinite, tabular halloysite and kickite by weight, and with smaller amounts of other 1:1 or non-expanding minerals or gibbsite (Soil Survey Staff, 1970). All the other soils fell below the A-line and denoted low plasticity. In this study, the soils with kaolinitic mineralogy fell below end near the A-line as in temperate sone soils; a few were slightly above the A-line but below the 50 percent liquid limits. The regression equation for Hawaiian soils with kaolinitic mineralogy is:

$$\text{Plasticity index} = -0.25 + 0.39 \times \text{liquid limit}$$

FIGURE 10. RELATIONSHIP OF ATTERBERG AND MINERALOGY



Conventional kaolinitic soils are generally referred to as clays that possess some of the characteristics of inorganic soils with low dry strength. This is, however, not true of Hawaiian kaolinitic soils even with liquid limits of more than 50 percent.

Kaolinitic soils were classified in the CL, ML, and MH group depending on their liquid limits and plasticity indexes. Most of these soils, however, fall in the MH or ML group.

Oxidic Family: Oxidic family is one with less than 90 percent quartz and less than 40 percent of any other single material and the ratio of $\frac{\text{\% extractable iron oxide and gibbsite}}{\text{\% clay}} = > 0.20$. The soils with oxidic mineralogy were somewhat scattered below the A-line and had liquid limits of more than 50 percent and plasticity indexes of less than 24 percent. The regression line of these soils was below that of the line for kaolinitic mineralogy and similar to that of medial mineralogy. The regression equation for soils with oxidic mineralogy is:

$$\text{Plasticity index} = -3.49 + 0.39 \times \text{liquid limit}$$

These soils were classified in the ML or MH groups with the majority falling in the ML group.

Medial Family: Soils formed from volcanic ash under relatively low rainfall have medial particle-size. Medial family is described as one with less than 60 percent by weight of volcanic ash, cinders, and pumice in the fine earth fraction, and this fraction is not thixotropic (Soil Survey Staff, 1970). The liquid limit of these soils ranged from 43 to 123 percent; the plasticity indexes ranged from 9 to 27 percent.

These soils were classified in the MH group.

Thixotropic Family: Thixotropy is described in Webster's dictionary as "a reversible gel-sol transformed under isothermal shearing stress following rest." The Hydrandepts and the Hydric Dystrandepts exhibit this property. Liquid limits ranged from 136 to 290 percent; plastic indexes for these soils ranged from 20 to 120 percent but generally were on the low side. The regression equation for this soil is:

$$\text{Plasticity index} = -23.21 + 0.40 \times \text{liquid limit}$$

Most of these soils have high organic matter content. Therefore, most of them were classified in the OH group. Others with less organic matter content were classified in the MH group. In general, soils developed from volcanic ash had liquid limits decreasing in the following order: thixotropic, medial and ashy families.

Mixed Family: The soils with mixed mineralogy varied from low to high liquid limits. Even a small amount of montmorillonite gave a soil characteristics of this mineral. Because of the numerous types of minerals in this family, it was difficult to make predictions on the behavior of these soils.

Soils with mixed mineralogy were classified in the CL or MH group.

Relationship between Modified Proctor Density and Unified Soil Groups

These soils were compacted with a 10-pound rammer and the maximum dry density was plotted against the optimum moisture. The regression equation for this relationship is:

$$\text{Dry density} = 142.5 + (-1.6 \times \text{optimum moisture})$$

To determine if there was any existence of relationship between the Proctor density and Unified soil groups, Collins* plotted maximum dry

*Unpublished data at the Soil Conservation Service Office.

density against optimum moisture. His results showed a grouping of ML, MH and CL groups with definite ranges in maximum dry density and optimum moisture for each group. Data compiled for this report shows MH soils below Line B; ML soils between Lines B and C; and CH and CL soils above Line C (Figure 11).

Kawano and Holmes (1958) compared compaction tests for five montmorillonitic and five kaolinitic clay soils in Hawaii. Their results failed to show that montmorillonite clays compacted more readily than kaolinite clays.

Townsend et al. (1971) suggested that the oxides of iron and aluminum influenced the behavior of a soil by coating the clays and binding them into coarser aggregates. He further believed that the granular structure of the soil gave a soil a lower density and a higher void ratio. However, the results of this study showed that the maximum dry density of Hawaiian soils were comparable to that of the temperate regions but had higher optimum moisture content. The high optimum moisture content was due to water held within the porous microaggregates (Townsend et al., 1971) and from that associated with the amorphous coatings around the soil.

Terzaghi (1958) stated that lateritic and temperate soils having similar liquid limits and plastic limits behaved differently because of the presence of microaggregate cluster of clays containing large amounts of goethite in lateritic soils.

<u>Relationship between Modified Proctor Density and Mineralogy</u>

The mineralogies of these soils were compared with the modified Proctor densities of the soils as shown in Figure 12. The optimum

FIGURE II. RELATIONSHIP BETWEEN DRY DENSITY, OPTIMUM MOISTURE AND UNIFIED GROUPS

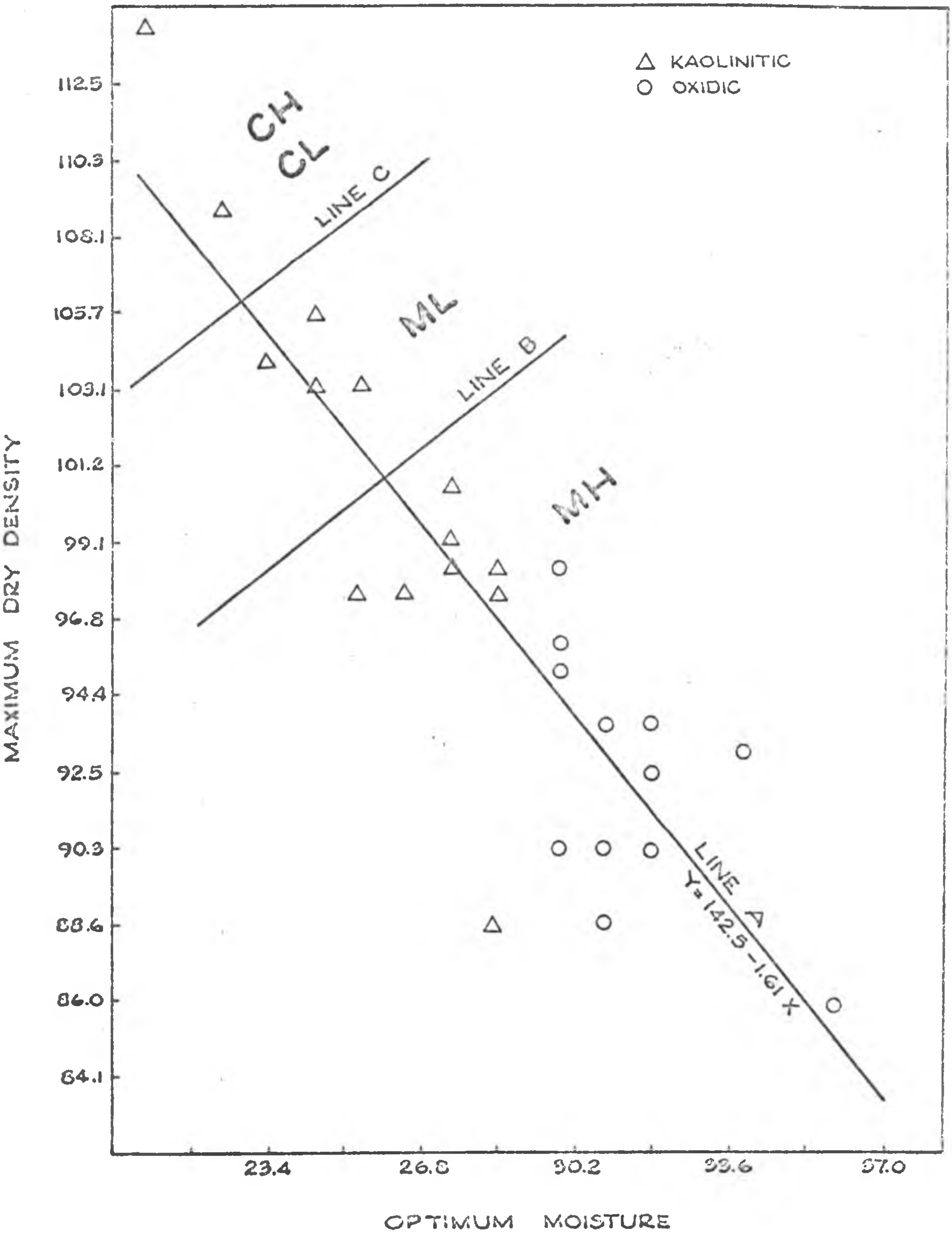
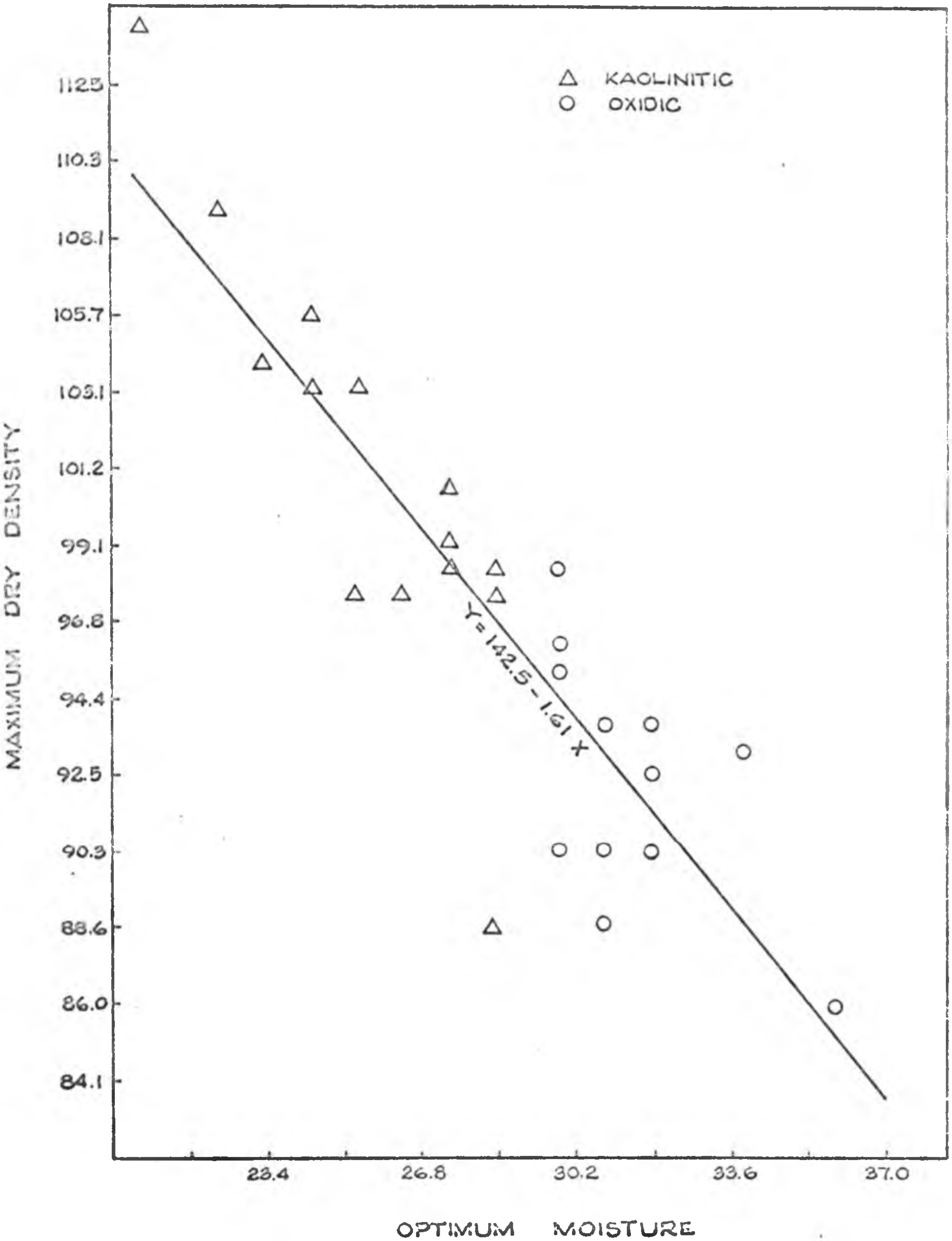


FIGURE 12. RELATIONSHIP BETWEEN MAXIMUM DRY DENSITY AND OPTIMUM MOISTURE



moisture content of oxidic soils was generally more than 30 percent while that of the kaolinitic soils was less than 30 percent. Kaolinitic soils showed quite low optimum moisture content even though they had a fairly high clay content.

The maximum dry density of these soils was also dependent upon mineralogy. The oxidic soils had a maximum dry density of less than 95 pounds per cubic foot, while that of kaolinitic soils generally had more than 95 pounds per cubic foot. This is probably due to the fineness of the oxidic clays which have a greater surface area, and therefore, more moisture content.

The optimum moisture content for all these Hawaiian soils, however, was much greater than those of temperate zone soils.

Relationship between Liquid Limit and Optimum Moisture

The optimum moisture content is related to texture and clay mineralogy. In fine grained soils, specific surface area is more important than gradation inasmuch as it usually indicates chemical activity and mineralogy. The shrink-swell potential, ease of compaction, and strength decreases as the optimum moisture increases. The above is true for soils whose behavior can be predicted by the Unified classification system.

For Hawaiian soils, this generalization does not hold. Large surface areas, associated with the smallness of the clay size, contributed to the high adsorptive capacity for water which is reflected in the high liquid limit and optimum moisture. These fine particles, however, are thoroughly cemented into aggregates by amorphous coatings. Thus, oxide soils possess properties of fine-grained material such as high liquid limits and optimum moisture on the one hand, and high strength of quartz grain soil on the other. The fineness of the particles of oxidic composition in relation to particles of kaolinitic clay mineral may be compared in the electron micrographs (Figures 13 and 14).

The soils with oxidic mineralogy have, in general, greater liquid limits and optimum moisture than soils with kaolinitic mineralogy. When the liquid limit and optimum moisture were plotted for soils of varying mineralogies, the points were scattered as shown in Figure 15. In general, the medial and montmorillonite have high liquid limits; the oxidic soils have intermediate liquid limits; and the kaolinitic soils have low liquid limits.

As the water content of the soil increases above optimum moisture, it becomes more difficult to excavate with ordinary earth moving equipment. At water contents exceeding optimum moisture of 10 percent, it would probably be necessary to excavate with drag lines rather than scrapers (Thornburn, 1966). This was exactly what the contractors did when constructing the Glenwood section of the new Volcano road on the island of Hawaii. Here, much of the area is occupied by the Akaka series, and OH soil with liquid limits of 290 percent and with thixotropic properties. The Hilo and Honokaa soils have lower liquid limits of about 150 percent. Scrapers can be used; however, because these soils have thixotropic properties, the tractors have been known to bog down after several passages over the same area.

Relationship between Plastic Index and Optimum Moisture and between Plastic Limit and Optimum Moisture

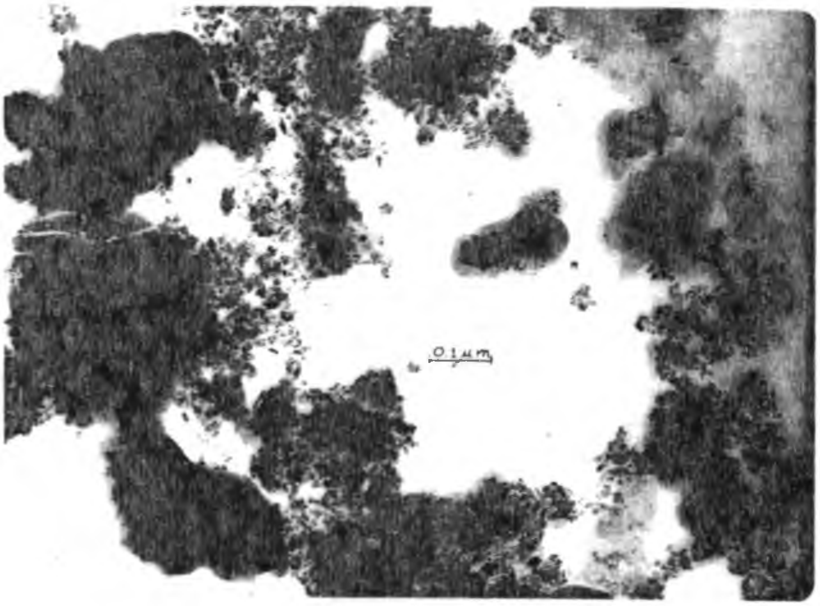


Figure 13. — Electron Micrograph of Clay Aggregates with Oxidic Mineralogy by R. Jones of University of Hawaii

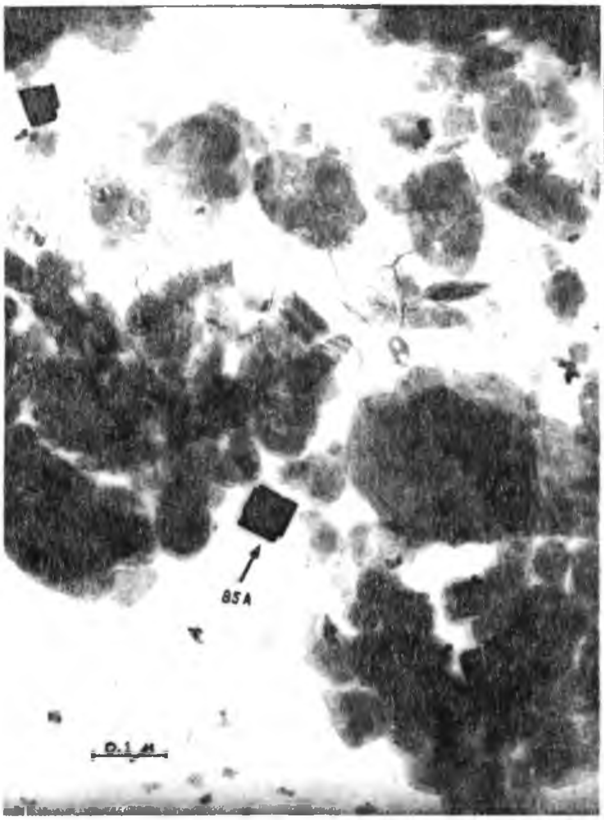
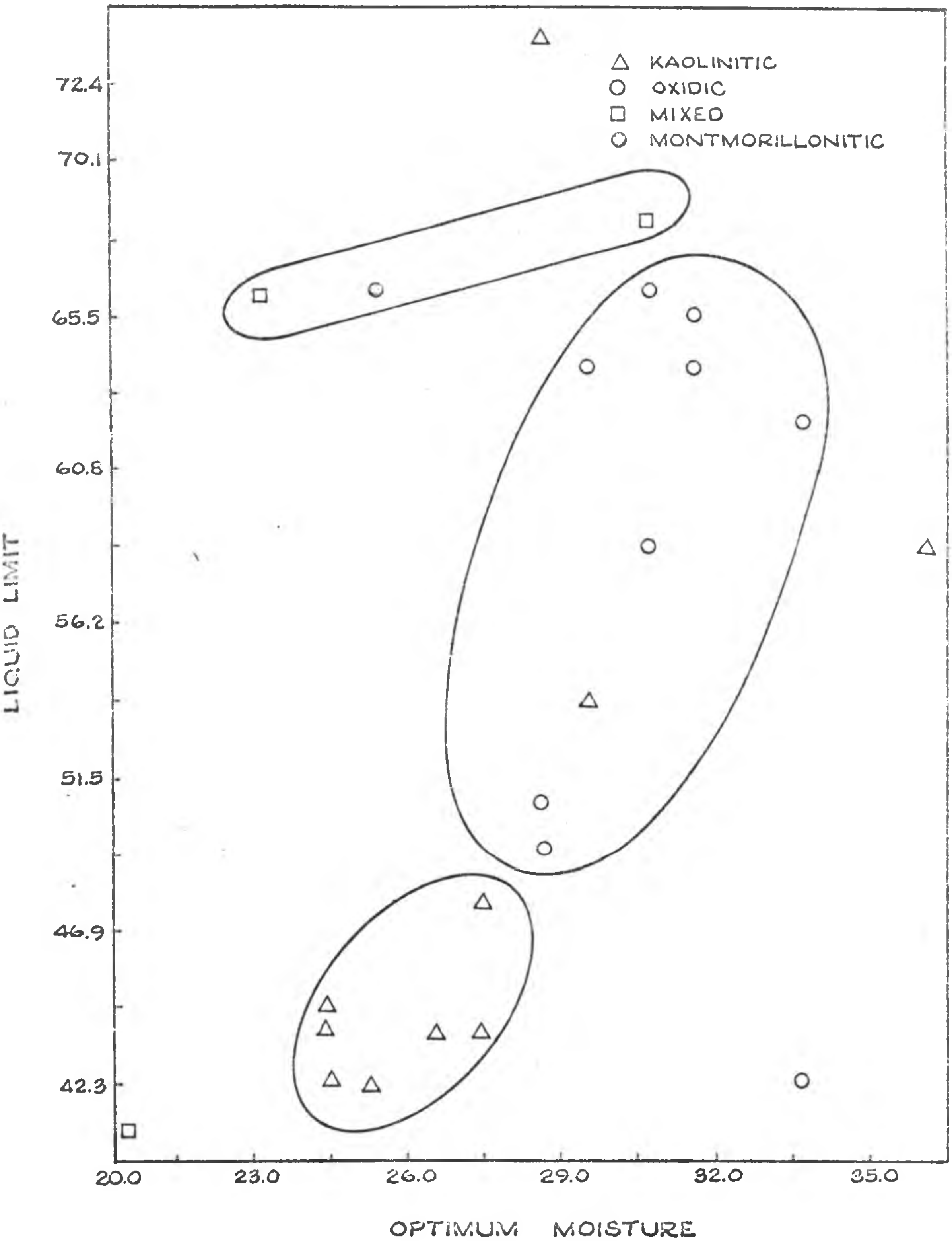


Figure 14. — Electron Micrograph of Clay Aggregates with Kaolinitic Mineralogy by R. Jones of University of Hawaii

FIGURE 15. RELATIONSHIP BETWEEN LIQUID LIMIT AND OPTIMUM MOISTURE



When the relationships between plasticity index and/or plastic limit and optimum moisture were compared, the optimum moisture for oxidic soils were higher than that for kaolinitic soils (Figure 16). Optimum moisture for oxidic soils was more than 29 percent while that of kaolinitic soils was less.

There was a correlation between high plasticity index and high shrink-swell potential and this was shown by such soils as Lualualei and Honouliuli series, members of the Typic Chromusterts.

Proposed Modification of the Unified Soil Classification System

Because of the numerous suggestions he received for expansion of his Unified soil classification system, Casagrande (1948) recommended the introduction of an I (intermediate) group for liquid limits between 35 to 50 percent and the addition of a kaolinitic subgroup as possibilities.

The soil data used in this study did not show liquid limits of less than 35 percent. Therefore, an I group has little value for Hawaiian soils.

In order to make the Unified system more useful for Hawaiian soils, it is proposed that a symbol H be placed before the Unified group. This will immediately show that this is a modification of the Unified system for Hawaiian soils. Furthermore, a letter denoting families for kaolinitic, oxidic, and montmorillonitic classes and thixotropic and medial particle-sizes should be added after the Unified groups because of the important role mineralogy plays in the behavior of Hawaiian soils. This proposed modification is presented in Table 6.

FIGURE 16. RELATIONSHIP BETWEEN PLASTICITY INDEX, PLASTIC LIMIT AND OPTIMUM MOISTURE

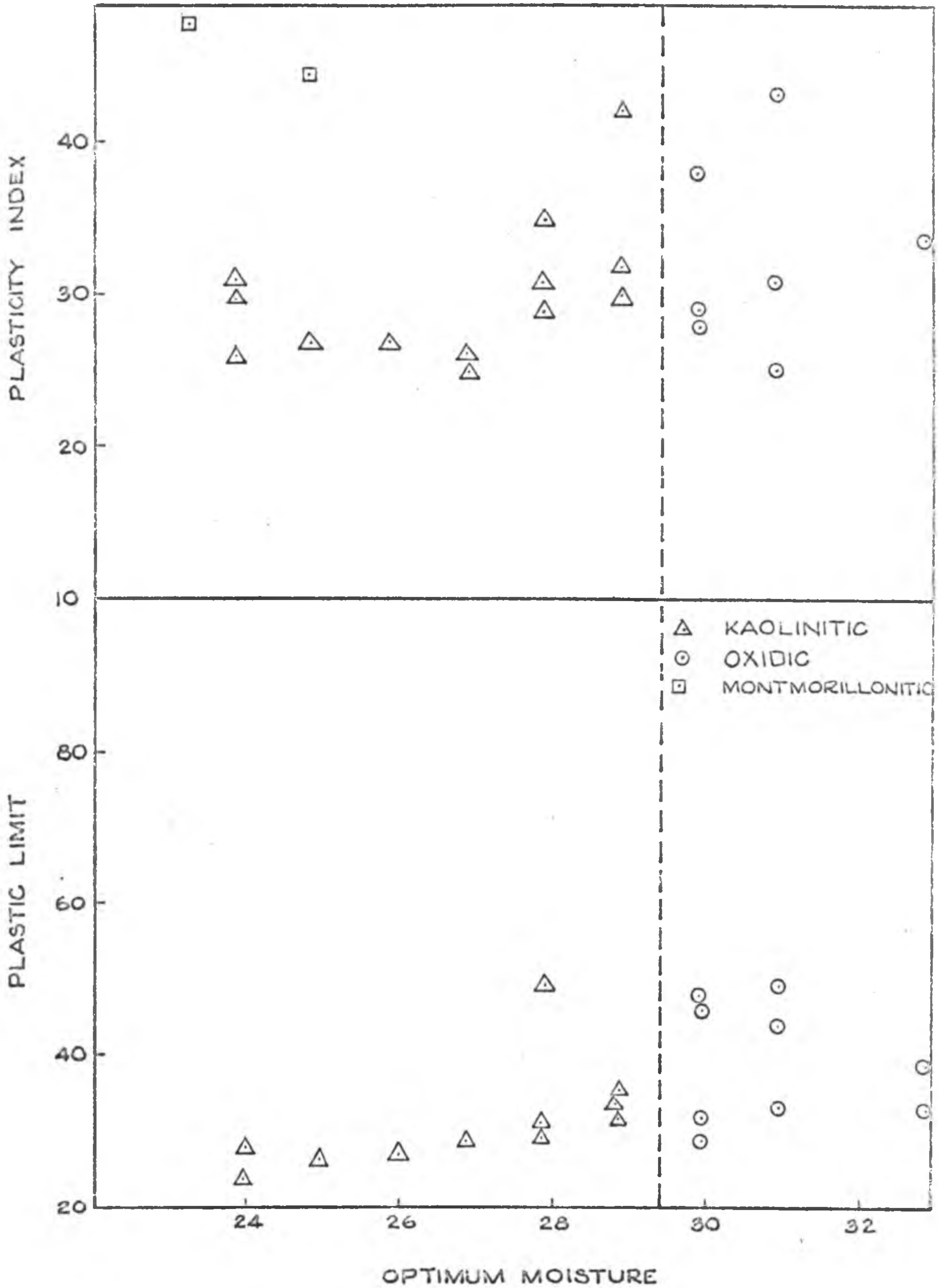


Table 6. -- Proposed Modification of the Unified Groups for Hawaiian Soils According to Mineralogy

Original Groups	Suggested Groups	Family Differentiae
CL	H - CL - M	Mixed
	H - CL - K	Kaolinitic
ML	H - ML - K	Kaolinitic
	H - ML - A	Medial
	H - ML - OX	Oxidic
OL	H - OL	Organic
CH	H - CH - MO	Montmorillonite
	H - MH - K	Kaolinitic
MH	H - MH - M	Mixed
	H - MH - A	Medial
	H - MH - T	Thixotropic
OH	H - OH	Organic

Soil Interpretations

The objectives of soil interpretation for engineering uses are to predict the performance of soils as construction material for roads, as sites for septic tanks, and as foundation material for houses and embankments. Predictions about a certain kind of soil are made through the understanding of its properties and through actual experience.

These predictions are useful even though there is no rational basis for them. A combination of experience, supported by field and laboratory date would be the ultimate basis for making predictions.

From personal experience, discussions with engineers, and publications (Tateishi, 1967; Lohner et al., 1968) an attempt is made in Table 7 to predict the behavior of the soils classified under the proposed modification of the Unified subgroups for Hawaiian soils.

Since the interpretations are made of the soil groups, proper soil classification becomes of vital importance. Verification of field identification by laboratory test should be made on representative samples (Kellogg, 1961).

The proper design of roads and embankments requires the evaluation of the soil properties in more detail than is given in the general soil classification system. Although the groupings of soils in the classification syetem gives a general indication of their behavior, there is no substitute for actual testing to determine the important engineering properties of a particular soil (Kellogg, 1961).

Table 7. -- Tentative Interpretation of the Behavior of the Proposed Modification of Unified Classes for Hawaiian Soils

Group Symbol	Compress-ability	Piping	Perme-ability	Compaction Character-istics	Value as Foundation
H - CL - M	Slight	Moderate to Low	Medium	Good	Good
H - CL - K	Slight	Low	Medium	Good	Good
H - ML - A	Slight to Moderate	Moderate	Medium to High	Fair to Good	Good to Fair
H - ML - K	Slight	Low	Medium	Good	Good
H - ML - OX	Slight	Low	Medium	Fair	Good to Fair
H - OL	High	Low	High	Poor	Poor
H - CH - MO	High	Low	Low	Good	Poor
H - MH - K	Slight	Low	Medium	Good	Good
H - MH - OX	Slight to Moderate	Low	Medium	Fair	Good to Fair
H - MH - M	Slight to Moderate	Low	Medium	Fair	Good
H - MH - A	Moderate	Low to Moderate	Medium to High	Fair	Fair to Good
H - MH - T	High to Moderate	Low	Medium to High	Poor	Fair
H - OH	High	Low	High	Poor	Poor

SUMMARY AND CONCLUSIONS

Currently used engineering soil classification systems predict that a large majority of Hawaiian soils possess poor properties as foundations for small structures. Experience in Hawaii indicates that these systems of classification in many cases underestimates the value of Hawaiian soils as engineering material.

This discrepancy between prediction and actual performance arises from the fact that the AASHO and Unified classification systems group soils largely on the basis of two rheologic parameters—the liquid limit and plastic limit. Soils with high liquid limits generally fall in soil categories which possess poor engineering properties. Most Hawaiian soils fall in this category.

High clay content of Hawaiian soils and the resultant high specific surface make it possible for soil material to adsorb large amounts of water. In many soils, however, the fine clay particles are cemented into aggregates which often behave as sands or gravels. Cementation of clay particles into stable sand-sized aggregate occurs in soils with kaolinitic and oxidic mineralogies. Aggregates of kaolinite and oxides of iron and aluminum do not expand when moistened and therefore do not disintegrate.

Soils with montmorillonite mineralogy have high dry strength because the dry aggregates have high strength. But upon wetting the clay, minerals swell, and the resultant swelling pressure causes aggregates to disintegrate.

Soils with montmorillonite mineralogy behave in ways predicted by current engineering soil classification systems. The failure of these systems to predict behavior of a large number of Hawaiian soils has probably caused wholesale rejection of their usefulness. This has resulted in construction of houses on soils, which were correctly assessed by engineering classification to be unsuited for homesites with costly consequences.

This thesis modifies the Unified soil classification system so that soils of the State of Hawaii may be more accurately evaluated for engineering uses.

To more correctly assess the Unified soil classes of Hawaiian soils, it is proposed that (1) a symbol H be placed before the regular Unified groups and (2) each Unified group be identified as to its mineralogy or particle-size classes so that its behavior can be more accurately predicted. The following family classes have been added after the Unified classes: kaolinitic, oxidic, medial, mixed, and thixotropic for each Unified group.

A table showing the behavior patterns of the proposed Hawaiian Unified classes according to mineralogy is recorded. These behavior patterns are based primarily on experience and should be tested closely.

More detailed, accurate information on the physical characteristics and properties of soils and their behavior under varied conditions need to be documented. When behavior and performance have been correlated and interpreted with soil characteristics, this information should prove to be helpful and valuable to Engineers and Land Use Planners.

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